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LEPTON-FLAVOR VIOLATION AT FUTURE LEPTON COLLIDERS AND THE ATMOSPHERIC NEUTRINO OSCILLATION[1]

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Abstract

It can be expected from the result for the atmospheric neutrino by the SUPERKAMIOKANDE and the CHOOZ result that the the lepton-flavor violating (LFV) interaction between the second and third generations exits at the high energy scale. This leads to a non-vanishing LFV left-handed slepton mass between the second and third generations, induced by the radiative correction, in the minimal supergravity scenario. In this article, assuming that the supersymmetric standard model with the right-handed neutrinos explains the atmospheric neutrino result, we show that the reach of the LFV slepton production in the future lepton colliders can be more significant than that of $\tau \to \mu\gamma$.

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The lepton-flavor violation (LFV) is one of the characteristic signatures in the supersymmetric (SUSY) extension of the Standard Model (SM). Introduction of supersymmetry to the SM is one of the promising idea beyond the SM, since it is a solution of the naturalness problem associated with the Higgs boson mass, as well-known. In order to make this model phenomenologically viable, we have to introduce the SUSY breaking terms. This may lead to the LFV by the gaps between the mass bases of sleptons and of leptons.

In the minimal supergravity scenario, which is the one of the candidates of the generation mechanism of the SUSY breaking in the SUSY SM, the magnitude of the LFV depends on the high energy physics beyond the SUSY SM. In this scenario, the slepton masses are degenerate and the lepton flavor is conserved at the tree level. However, if the LFV interaction at the high energy scale, such as the Yukawa interaction of the right-handed neutrinos, exits, the radiative correction to the slepton masses is lepton-flavor violating [1, 2].

The SUPERKAMIOKANDE provided the convincing result for the atmospheric neutrino anomaly, and showed that it comes from the neutrino oscillation [3]. Combined with the CHOOZ experiment [4], it is natural to consider that the oscillation is between the muon and the tau neutrinos, and

$$\begin{aligned} \Delta m^2_{\nu_\mu\nu_\tau} &\simeq (5\times 10^{-4} - 6\times 10^{-3})\mathrm{eV}^2, \\ \sin^2 2\theta_{\nu_\mu\nu_\tau} &> 0.82. \end{aligned} \tag{1}$$

This means that the LFV interaction, such as the Yukawa coupling of the right-handed neutrino in the see-saw mechanism [5], exits in order to generate the small neutrino masses, and that the LFV between the second and the third generations in the slepton mass matrix is generated in the minimal supergravity scenario.

The ways to study the LFV between the second and third generations in the SUSY SM are *i*) the LFV radiative processes such as $\tau \to \mu\gamma$ and *ii*) the LFV slepton production processes in the future colliders with the signal $\tau\mu X\ \not{E}$ [6, 7]. In this article we compare the reach of the LFV slepton production in the future lepton colliders with that of $\tau \to \mu\gamma$, assuming that the SUSY SM with the right-handed neutrinos explains the atmospheric neutrino result. Due to low statistics of the $\tau \to \mu\gamma$ experiments and the weak GIM suppressions in the LFV production processes of slepton, search for the LFV slepton production in the future lepton colliders can be more significant than the future

experiment of $\tau \to \mu\gamma$.

First, we will review the MSSM with the right-handed neutrinos, and discuss the radiative generation of the LFV in this model. The see-saw mechanism by introducing the right-handed neutrinos is the simplest idea to generate the small neutrino masses. The superpotential of the lepton sector in the SUSY SM with the right-handed neutrinos is

$$W_{\mathrm{MSSM}+\nu_{\mathrm{R}}} = f_{\nu_i} U_{Dij} H_2 N_i^c L_j + f_{l_i} H_1 E_i^c L_j + \frac{1}{2} M_{ij} N_i^c N_j^c, \tag{2}$$

where L is the chiral superfield for the left-handed leptons, and N^c and E^c are those for the right-handed neutrinos and charged leptons. H_1 and H_2 are the Higgs doublets in the MSSM. Here, i and j are generation indices. A unitary matrix U_D is similar to the Cabibbo-Kobayashi-Maskawa (CKM) matrix in the quark sector. In this model the mass matrix for the left-handed neutrinos is given as

$$(m_{\nu_L})_{ij} = U^T_{Dik} (\overline{m}_{\nu_L})_{kl} U_{Dlj} \tag{3}$$

where $(\overline{m}_{\nu_L})_{ij} = [M^{-1}]_{ij} f_{\nu_i} f_{\nu_j} \langle H_2 \rangle^2$. The large mixing angle in the atmospheric neutrino result (Eq. 1) comes from the unitary matrix U_{D32} or the neutrino mass matrix $(\overline{m}_{\nu_L})$. As we will show later, if U_{D32} is of the order of one, the LFV in the SUSY SM is enhanced.

The Yukawa interaction of the neutrino given in Eq. 2 generates the LFV masses for the left-handed sleptons radiatively [1]. At the logarithmic approximation of one-loop level, the mass matrix of the left-handed slepton $(m^2_{\tilde{L}})$ is given as

$$(m^2_{\tilde{L}}) \;=\; U_D^\dagger \begin{pmatrix} \overline{m}^2 & & \\ & \overline{m}^2 & \\ & & \overline{m}^2 - \Delta m^2 \end{pmatrix} U_D. \tag{4}$$

Here, $\Delta m^2 = \frac{1}{4\pi^2} f^2_{\nu_\tau} (3 + a_0^2) m_0^2 \log \frac{M_{\mathrm{G}}}{M_{\nu_R}}$, where m_0^2 and a_0 are the universal SUSY breaking scalar mass and the SUSY breaking trilinear coupling in the minimal supergravity scenario. M_{G} and M_{ν_R} are the gravitational and the right-handed neutrino mass scales. If f_{ν_τ} and/or U_{D32} are sufficiently large, $(m^2_{\tilde{L}})_{23}$ is enhanced.[1]

The ways to probe $(m^2_{\tilde{L}})_{23}$ are $\tau \to \mu\gamma$ [8] and the LFV production processes of the left-handed sleptons [9], as we mentioned before. The LFV production of the left-handed

[1] The right-handed sleptons cannot get the sizable LFV masses from the radiative correction in this model since the right-handed leptons are not coupled with the right-handed neutrinos.

slepton has statistical merits. First, this comes from tree-level diagrams while $\tau \to \mu\gamma$ is a one-loop process. Second, the GIM suppression factor in the LFV slepton production is at most $(\Delta m^2/\overline{m}\Gamma)^2$ with Γ the slepton width due to the slepton oscillation [7] while the suppression factor in $\tau \to \mu\gamma$ is $(\Delta m^2/\overline{m}^2)^2$. If the mass difference of the left-handed sleptons is larger than the width, which is about 1GeV, the suppression factor in the LFV slepton production is not effective. In Fig. 1 we show the mass difference $\Delta m_{\tilde{\nu}}$ and the mixing angle $\sin 2\theta_{\tilde{\nu}}$ between the tau and muon sneutrino as a function of the right-handed neutrino scale M_{ν_R} in the SUSY SM with the right-handed neutrinos. Here, we take $m_{\nu_\tau} = 7 \times 10^{-2}$ eV and $U_{D32} = 1/\sqrt{2}$. Also, $m_{\tilde{\nu}_\mu} = 180$ GeV, the wino-like chargino mass 100GeV, $\tan\beta = 3$, 10, 30, and the other parameters are determined in the minimal supergravity scenario. If M_{ν_R} is larger than 10^{13}GeV, $\Delta m_{\tilde{\nu}}$ is larger than 1 GeV [9].

The LFV signals in the direct production of the left-handed sleptons in the $\mathrm{e}^+\mathrm{e}^-$ collider and the muon collider depend on the mass spectrum of the SUSY particles. In the minimal supergravity scenario, the left-handed sleptons and sneutrinos tend to be heavier than the wino-like chargino or the wino-like neutralino. In this case, the LFV signal with the largest cross section is

$$\mathrm{e}^+\mathrm{e}^-(\mu^+\mu^-) \;\; \to \;\; \tilde{\nu}\tilde{\nu}^c \text{ or } \tilde{l}^+\tilde{l}^- \to \tau\mu + 4jets + \not{E}. \tag{5}$$

The jets in the final states come from the decay of the wino-like chargino and neutralino. The backgrands from the SM processes are significantly small since the signal has multi-activities. The most significant backgrand comes from processes where a tau lepton, which is one of the tau pair in the tau slepton and sneutrino production, decays into a muon. In order to reduce this backgrand sufficiently, we need to enhance the muon and tau lepton identification rates. The energy and impact parameter cuts for muons are effective for the purpose [9].

In Fig. 2 we show the significance contours corresponding to 3σ discovery as functions of $\sin 2\theta_{\tilde{\nu}}$ and $\Delta m_{\tilde{\nu}}$. The dashed-dot (solid) line is for $\mathrm{e}^+\mathrm{e}^-$ $(\mu^+\mu^-)$ colliders with the center mass energy 500GeV. We assume the integrated luminosity $\mathcal{L} = 50\mathrm{fb}^{-1}$. For the $\mathrm{e}^+\mathrm{e}^-$ collider we take the impact parameter cut for muons as $\sigma_{IP}^{\mathrm{cut}} = 10\mu m$. Here, $m_{\tilde{\nu}_\mu} = 180$ GeV, the wino-like chargino mass 100GeV, and $\tan\beta = 3$. The other parameters are determined in the minimal supergravity scenario. The long dashed lines are for the

branching ratio of $\tau \to \mu\gamma$, 10^{-7}, 10^{-8}, 10^{-9}, and 10^{-10}. Then, the 3σ significances for $\mathrm{e^+e^-}$ collider and the muon collider with the integrated luminosities $\mathcal{L} = 50 fb^{-1}$ correspond to $\mathrm{Br}(\tau \to \mu\gamma) \sim 10^{-9}$ and 10^{-10}, respectively, for $\tan\beta = 3$[2] [9].

When $\tan\beta$ is large, $\mathrm{Br}(\tau \to \mu\gamma)$ is proportional to $\tan^2\beta$. On the other hand, the LFV slepton production is not significantly changed, since the mass difference of slepton is enhanced while the mixing angle is reduced (see Fig. 1). The future prospect of the reach of $\mathrm{Br}(\tau \to \mu\gamma)$ is at most 10^{-8} at present. Then, search for the LFV signal in the slepton production is powerful in the small $\tan\beta$.

In this article, we compared the reach of search for the LFV slepton production with that of $\tau \to \mu\gamma$, concentrating on a case that the LFV mass for the left-handed sleptons $(m^2_{\tilde{L}})_{23}$ is induced in the SUSY SM with the right-handed neutrinos. We showed that the search for the LFV slepton production in the future lepton colliders can be more significant in the LFV study than the future experiment of $\tau \to \mu\gamma$.

[2] The difference of the significances in the $\mathrm{e^+e^-}$ collider and the muon collider comes from a fact that the smuon and muon sneutrino production cross sections are enhanced by the t-channel exchange of the gauginos in the muon collider. If the integrated luminosity of the $\mathrm{e^+e^-}$ collider can reach to $1000 fb^{-1}$, it can compete with the muon collider with $\mathcal{L} = 50 fb^{-1}$.

References

[1] F. Borzumati and A. Masiero, *Phys. Rev. Lett.* **57**, 961 (1986).

[2] L. Hall, V. Kostelecky, and S. Raby, *Nucl. Phys.* B **267**, 415 (1986).

[3] Super-Kamiokande Collaboration (Y. Fukuda et al.), *Phys. Rev. Lett.* **81**, 1562 (1998).

[4] CHOOZ Collaboration, *Phys. Lett.* B **420**, 397 (1998).

[5] T. Yanagida, in *Proceedings of the Workshop on Unified Theory and Baryon Number of the Universe*, eds. O. Sawada and A. Sugamoto (KEK, 1979) p.95;
M. Gell-Mann, P. Ramond, and R. Slansky, in *Supergravity*, eds. P. van Nieuwenhuizen and D. Freedman (North Holland, Amsterdam, 1979).

[6] N.V. Krasnikov, *Mod. Phys. Lett.* A **9**, 1994 (791).

[7] N. Arkani-Hamed, H.-C. Cheng, J.L. Feng, and L.J. Hall, *Phys. Rev. Lett.* **77**, 1937 (1996).

[8] J. Hisano, T. Moroi, K. Tobe, M. Yamaguchi, and T. Yanagida, *Phys. Lett.* B **357**, 579 (1995);
J. Hisano, T. Moroi, K. Tobe, and M. Yamaguchi, *Phys. Rev.* D **53**, 2442 (1996);
J. Hisano and D. Nomura, *Phys. Rev.* D **59**, 116003 (1999).

[9] J. Hisano, M.M. Nojiri, Y. Shimizu, and M. Tanaka, hep-ph/9808410.

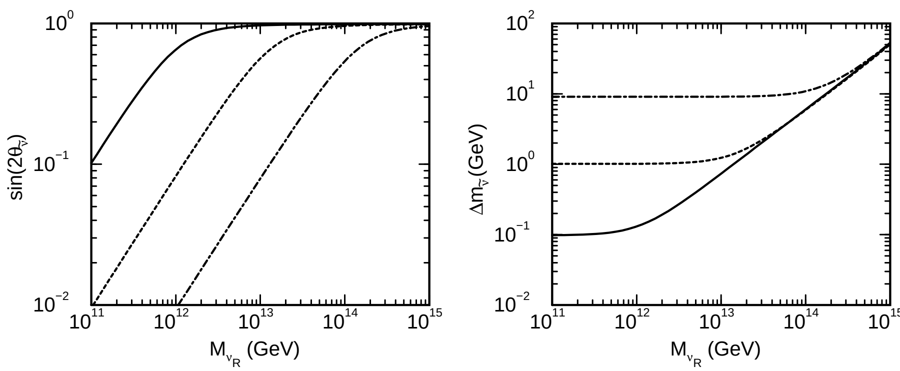

Figure 1: The mass difference $\Delta m_{\tilde{\nu}}$ and the mixing angle $\sin 2\theta_{\tilde{\nu}}$ for the tau and muon sneutrino as a function of the right-handed neutrino scale in the SUSY SM with the right-handed neutrino, taking account into the atmospheric neutrino result. Solid lines, dotted lines, and dash-dotted lines are for $\tan\beta = 3$, 10, 30, respectively.

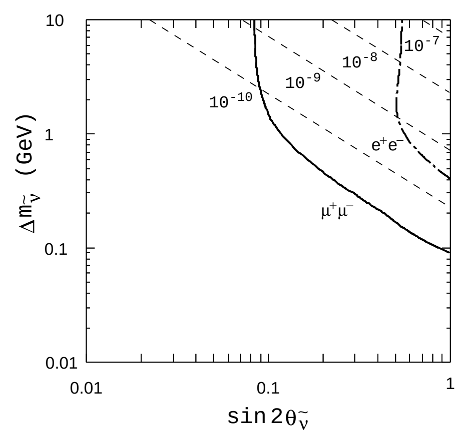

Figure 2: Significance contours corresponding to 3σ discovery as functions of $\sin 2\theta_{\tilde{\nu}}$ and $\Delta m_{\tilde{\nu}}$ in the $\mathrm{e^+e^-}$ collider (solid line) and the muon collider (dashed-dotted line) with $\sqrt{s} = 500\mathrm{GeV}$, $\mathcal{L} = 50 fb^{-1}$. The long dashed lines are for the branching ratios of $\tau \rightarrow \mu\gamma$ 10^{-7}, 10^{-8}, 10^{-9}, and 10^{-10}.